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DEVELOPMENT, CALUCLATION, AND PLANNING OF

HELICAL NEUTRON CHOPPER

by G. Ionescu

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OF HELICAL NEUTRON CHOPPER

-Rumania-

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1. INTRODUCTION

The first device used for the selection of neutrons was the neutron chopper built in 1947 by E. Fermi, J. Marshall, and L. Marshall [1], following an idea of Pegram and Fink [2] (fig. 1).

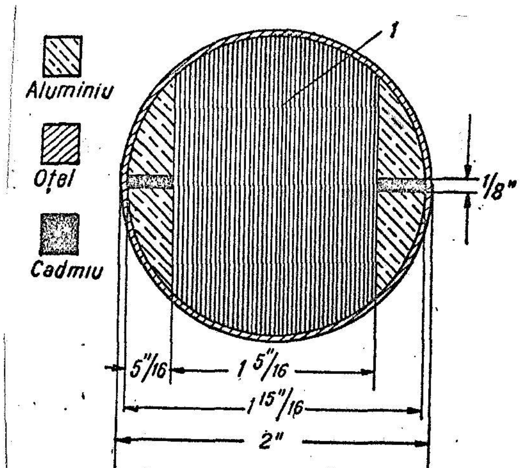

Fig. 1. Vertical section through chopper built by E. Fermi, J. Marshall, and L. Marshall (1" = 25.4 mm). [aluminiu = aluminum; otel = steel; cadmiu = cadmium.]

A new type of selector, nearer in concept to the helical selector, was the selector of W. Selove [3], built in 1952 (fig. 2). It was essentially a greatly elongated chopper set with its axis parallel to the direction of the neutron beam (the axis of the chopper is perpendicular to the beam). The functioning of this selector is wholly analogous to the functioning of the Fermi chopper, it having a passage characteristic of the "low-pass filter" type and permitting the passage only of pulses which contain neutrons of a speed higher than a certain lower limit speed called chopping speed and given by the relation

$$v_t = \frac{\omega L}{\varphi}, \tag{1}$$

in which ω is the angular velocity of the rotor, and L and φ are two quantities shown in figure 2.

Both the chopper and the Selove selector use the transit time method and electronic time analyzers.

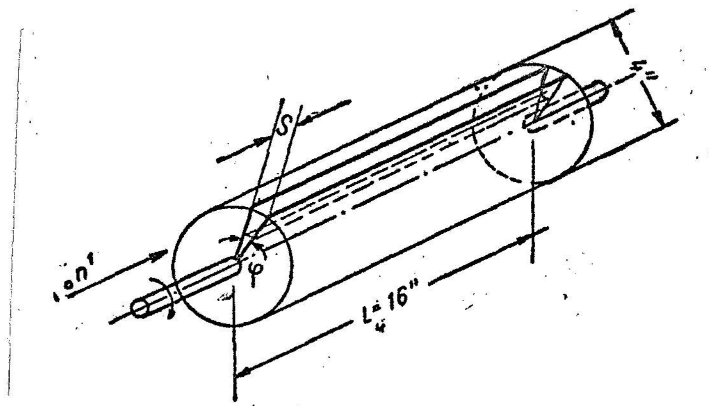

Fig. 2. The Selector of W. Selove.

In 1953 J. G. Dash and H. S. Sommers [4] conceived the idea of setting Selove's rotor at an angle to the beam, as shown in figure 3a; this arrangement is equivalent to designing a rotor with oblique channels (fig. 3b) (in fig. 3a the axis of the cylinder and the direction of the beam are parallel to the plane of the drawing).

Five years later, N. Holt [5] designed a combined selector made up of a crystal monochromator and a helical selector (fig. 4). This device was also used, by the way, by Dash and Sommers [4] to measure the transmission function of the selector designed by them, by reference to the known characteristics of the crystal. Such was the evolutional process which led to designing of the helical selector, which functions without an electric analyzer and no longer employs the transit time method as does the Fermi chopper. One may nevertheless speak of "transit time" within the selector itself, as we shall see presently.

Although the idea of using several disks opaque to neutrons, with holes (transparent to neutrons) phase-shifted in space (fig. 5) to select neutrons by synchronous rotation of the disks, had been known for a long time, the designing of such selectors was not reported until 1958 [6], [10].

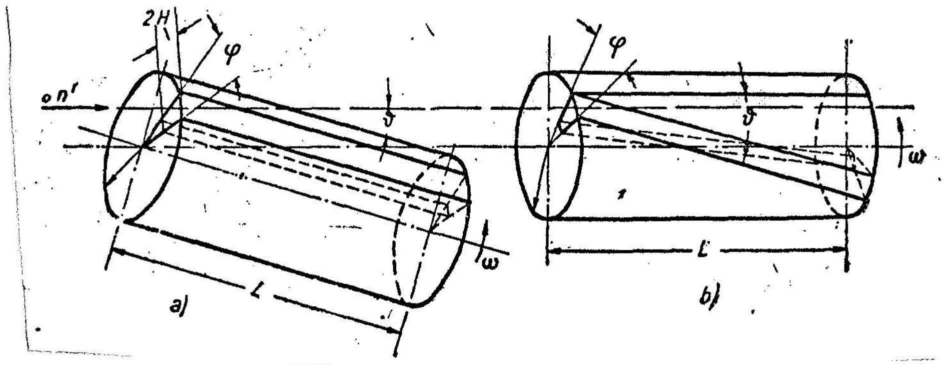

Fig. 3. Equivalence of rotor with straight channels set at an angle (a) and rotor with oblique channels set in the direction of the neutron beam (b).

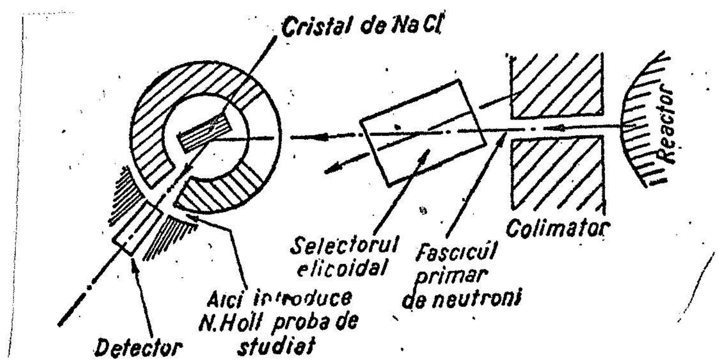

Fig. 4. Device for monochromatization of neutrons used by N. Holt. [Cristal de Na Cl = Na Cl crystal; colimator = collimator; selectorul elicoidal = helical selector; fascicul primar de neutroni = primary neutron beam; aici introduce N. Holl proba de studiat = N. Holl introduces test specimen here].

It would appear that this device, in which the disposition of the holes in space describes a helix, should lead directly to the helical neutron selector. However, the transition to the helical selector came about otherwise: directly from the Fermi chopper, as we have already seen.

The selector functions as follows:

The axis of the cylinder with straight channels being set at a certain angle to the direction of the neutron beam (fig. 3a), the device acts as a neutron monochromator. It can be seen in figure 6 how the neutrons with speeds which are "too high" collide with the wall 1 of the channel and are absorbed, while the neutrons with speeds which are "too low" collide with wall 3, the rotating cylinder thus acting as a neutron monochromator [See Note].

([Note]) The term "monocromatizator" ["monochromatizer"], from "a monocromatiza" ["to monochromatize"], is also used.

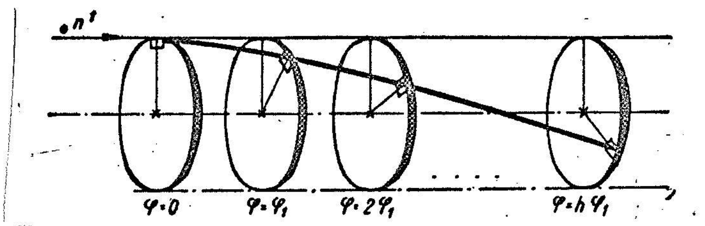

Fig. 5. Neutron monochromatization device made up of synchronously rotating disks with holes phase shifted through angle φ_1.

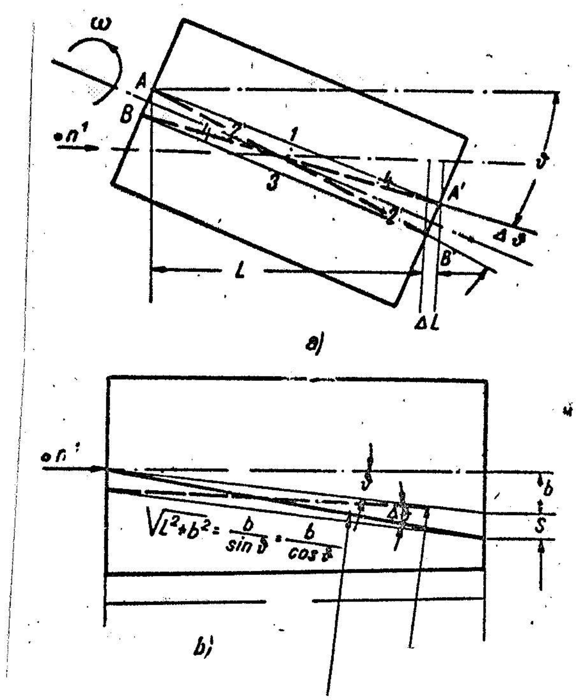

Fig. 6. Sketches for calculation of resolving power. [Traectoria neutronilor celor mai rapizi = Path of fastest neutrons; Traectoria neutronilor mai lenţi = Path of slowest neutrons].

The condition which must be fulfilled so that the neutrons may pass through the selector is that the points of the channel coincide in succession and uniformly in time with the path of the neutrons, which is a straight line. The form of the channel is then identical with the path of the neutrons in a mobile system of axes rigidly connected to the rotating cylinder, the transformation being given:

<u>in the fixed system by</u>:

$$Z = vt,\quad X = r,\quad Y = 0,$$

<u>in the mobile system by</u>:

$$(2)\quad \begin{cases} Z' = vt, \\ X' = x\cos\vartheta - y\sin y = \\ \quad = r\cos\vartheta, \\ Y' = x\sin\vartheta + y\cos\vartheta = \\ \quad = r\sin\vartheta, \end{cases}$$

in which $\theta\ \vartheta = \omega t$.

It is to be seen from this that the path equation in the mobile system is a helix. This helix can be approximated by a line which forms an angle θ with the generatrix of the cylinder (with the corresponding error).

2. REPRESENTATION OF EXISTING HELICAL SELECTORS

The first cylindrical selector (that of Selove, 1952) had six channels. A year later, Dash and Sommers designed a selector with 120 channels. N. Holt's selector [5], built in 1957, had only 80 channels.

The structure of the selectors has developed also: while the channels of the Selove selector were incrusted in the body of the cylinder, the Dash and Sommers selector employed holes formed by the radial disposition of fins, the holes being of 0.03 cm on the circumference of the cylinder in the Selove selector, and $\frac{1}{2}$ inch x 0.045 inch in that of Dash and Sommers (one inch = 25.4 mm). In the Holt selector the holes are made up directly by the space between two successive cadmium-plated fins. To permit evaluation of the size of the hole with relation to the thickness of the material between holes, Holt gives the fin thickness (1/16 inch) and the number of fins (80).

To simplify the presentation, we give a concise tabulation of the characteristics of all these selectors.

Table

Characteristics of Helical Selectors

Type / Characteristics	Selove [3], 1952	Dash and Sommers [4], 1953	Holt [5], 1957
Number of channels	6	120	80
Dimensions	0.03 cm on circumference of rotor	1 inch x 0.045 inch (25.4 mm x 1.14 mm)	2 inches x 0.5 inch (50 mm x 12.7 mm)
Transmission coefficient	10^{-3}	60%	80%
Rotor opacity	—	7×10^{-7}	10^{-10} (together with accessory crystal, v. fig. 4)
Power of drive motor	3 hp	0.5 hp	$\frac{1}{4}$ hp
Detection	3 BF_3 chambers 1 inch (in diameter) x 30 cm (in length); diameter of central electrode, 1/8 inch; pressure of interior gas, 2 atm	detector 1 inch (in diameter) x 12 inches (in length) with enriched BF_3	BF_3 counter
Calibration of device	Not indicated	with 2 x 2 x $\frac{1}{2}$ cubic inch NaCl crystal (v. fig. 4); crystal fixed on rotary table, calibration with use of n_0^1 of 1.5 Å.	with crystal as in preceding case
Rotor speed	Variable around 3,000 rpm	3,000 — 5,000 rpm	3,600 rpm
Quality factor	Approximately the same as with Dash-Sommers	~0.8	0.2 — 0.4

3. REPRESENTATION OF EXISTING DISK SELECTORS

The designing of disk selectors with holes phase shifted in space was undertaken simultaneously with the study of low-energy ("cold") neutrons. In these selectors the disks are arranged on the same axis, being rotated simultaneously by the same rotor; this eliminates the necessity of synchronization. Such a design is no longer possible in the case of neutrons of higher energy, inasmuch as the distances between the disks would be much greater and it would be necessary to drive them with several motors, this presupposing synchronization of the speeds. In practice, all these structural difficulties have the result that disk monochromators are designed only for low energies. The disk design (with the holes in the disks describing a helix which coincides with the path of the neutrons) is preferred because of the simplification of the technological process and the selector design as compared with the case of the helical selector properly so called. There is basically no difference between the two cases, provided the number of disks is large enough for definition of the helical channel with good precision.

The first device of this type which we shall discuss is the mechanical selector for slow neutrons designed by B. Jacrot and G. Gobert [6], [7] and used for the energy range of 10^{-2} to 10^{-4} ev. The effective cross-sections of materials in the low-energy range (subthermal and cold neutrons) will be measured with the aid of this selector.

In essence the rotor is made up of two rotors (disks) one meter in diameter spaced at intervals of one meter. There are openings in these disks shifted through an angle φ (fig. 7), the device being of the "shifted opening disk" type. The whole unit is mounted in an evacuated space so as to avoid friction with air. To make possible a comparison with the devices already described, we give the characteristics of this selector below:

weight of each disk	135 kg
diameter of disk	1 m
distance between disks	1 m
speed of rotation	6,000 rpm

At this speed the length of one neutron pulse is 50 μs (more exactly, the pulse half-width), the half-width in energy being 0.2 Å if we assume that the neutron beam is collimated and perfectly parallel. There are eight 15 x 50 mm^2 openings in each disk.

To afford an idea of the complexity of the installation, we reproduce from [8] a general view of this selector (fig. 8); the two disks may be seen on the left in the photograph.

The actuation, stabilization, and synchronization system of the whole unit consists of a complete series of gears and eight electric motors and generators consuming a total power of several kilowatts.

The paper gives a large number of structural details which can be of positive value to persons designing selectors of these types. On the other hand, no information whatever is given on the calculation and physical performance of this selector.

The selector designed by P. Hubert, R. Joly, and C. Signarbieux is made up of four disks mounted on the same shaft, the distance between the end disks equalling 100 cm, the diameter of the disks 60 cm, and the maximum speed of rotation 3,000 rpm, because of material strength considerations [8] (fig. 9).

The selector is designed to eliminate neutrons which undergo Bragg reflections of an order higher than one, and operates in conjunction with a crystal spectrometer. For this reason, the luminescence of the selector must be as great as possible. In the present instance it is 43%.

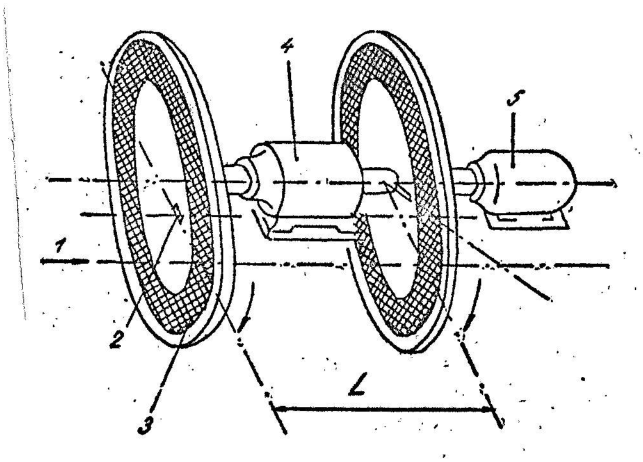

Fig. 7. Basic diagram of mechanical selector designed by Jacrot and Gobert: 1 — neutron beam; 2 — optical aperture; 3 — cadmium ring; 4 — mechanical phase shifter; 5 — electric motor.

The upper limit of utilization in energy of the selector is 0.03 ev (at 2,800 rpm). In each disk there are 66 openings 2°22' in width, the interval between openings being 5°27'. It has been assumed that the neutron beam has a divergence of 1/250 radian (straight collimator 250 cm in length and 1 cm in width). Each disk consists of two plates of duralumin 2 mm thick between which an 0.7 mm thickness of cadmium is inserted, the whole being cemented with araldite.

The selector designed by H. M. Skarsgard and C. J. Kenward [9] is shown in figure 10. This selector also consists of four disks, equally spaced, the interval between two successive openings being 0.106 radian (6°6'). The speed of rotation is continuously variable from 600 to 5,650 rpm, this corresponding to an energy range of 0.00059 to 0.051 ev. A $1\frac{1}{2}$-hp motor was used. The transmission of the selector for a well collimated beam is 38%. Tests have shown that the high order neutron intensity is reduced 10^3 times; the selector is used together with a crystal spectrometer (reflection on plane 200 of a KCl crystal). Up to energies of 0.05 ev the high order intensities are less than 0.05% of the first order intensities.

According to the authors cited above, the relationship of the speed of rotation to the neutron energy for which the transmission is the maximum is given by the formula

$$N\,(\text{rot/min}) = 2{,}5.10^4\sqrt{E}\,(\text{eV}). \qquad (3)$$

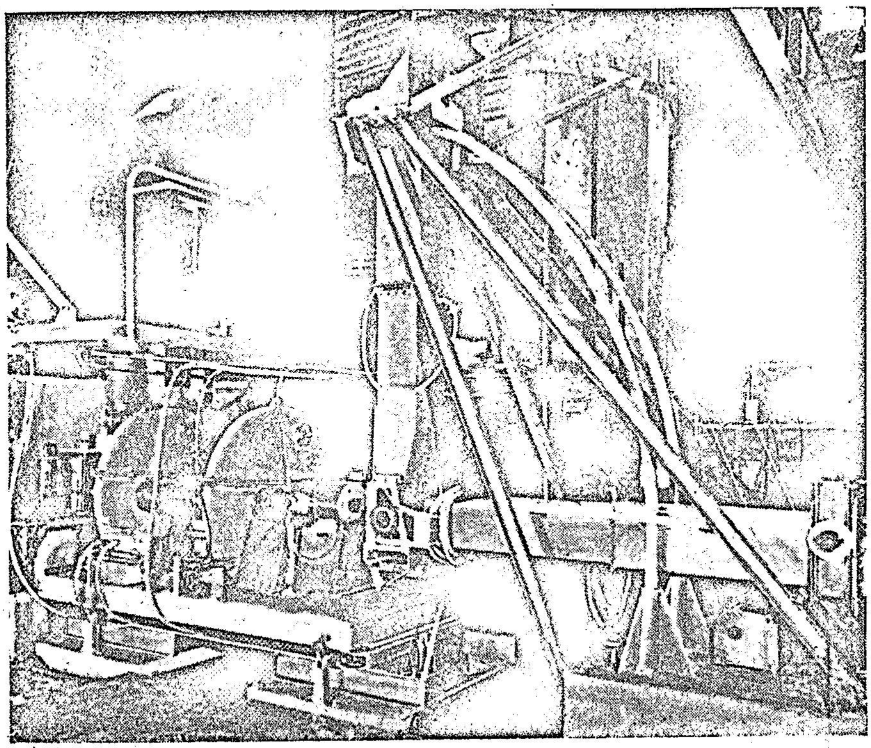

Fig. 8. General view of selector designed by Jacrot and Gobert.

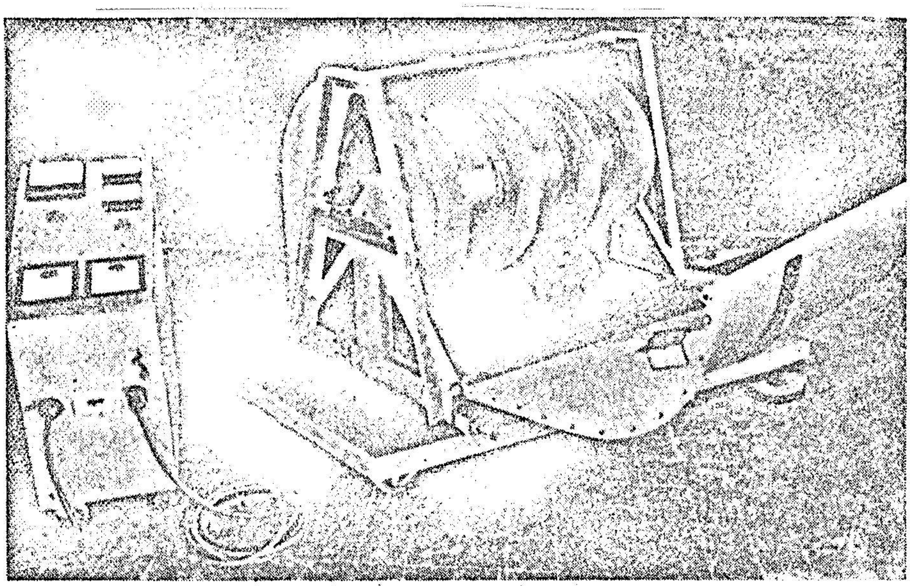

Fig. 9. Selector designed by Hubert, Joly, and Signarbieux.

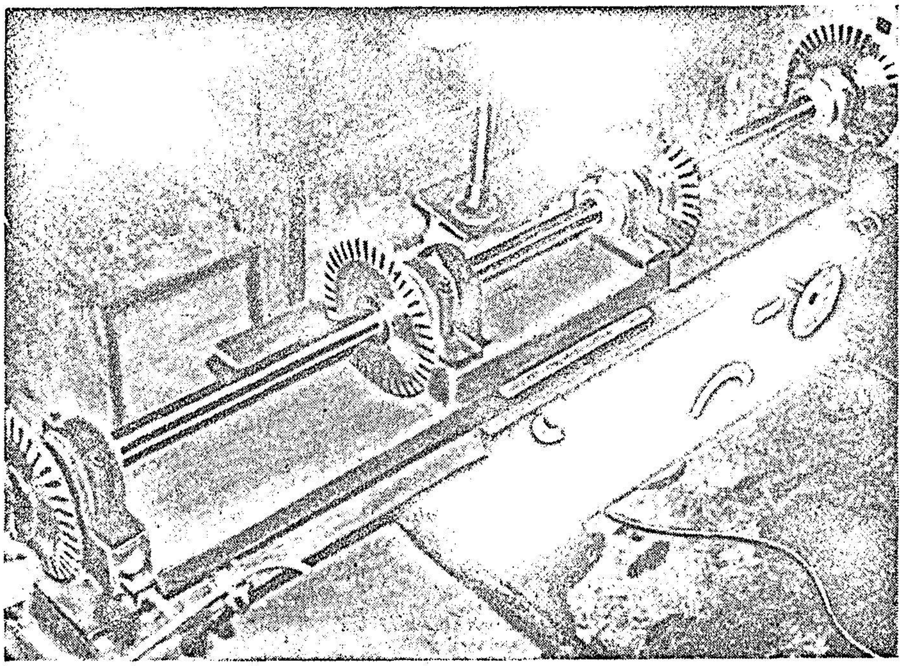

Fig. 10. Selector designed by Skarsgard and Kenward.

The detailed section of one of the disks is shown in figure 11. The disks are made up of plates of aluminum between which sheets of cadmium 0.030 inch thick are inserted. The shaft is 66 inches (1.675 meter) in length, the distance between disks being 25 inches (about 56 cm).

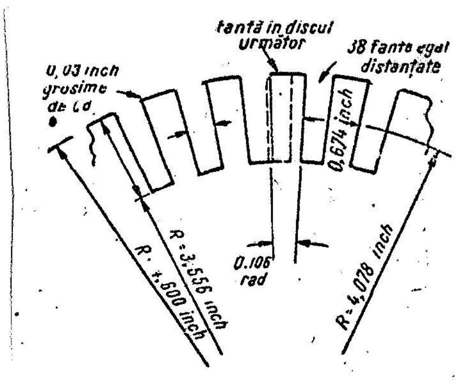

Fig. 11. Detailed sketch of portion of disk (after [9]). [0.03 inch grosime de Cd = 0.03 inch thickness of cadmium; fanta in discul urmator = opening in following disk; 38 fante egal distantate = 38 equally spaced openings.]

Another recently reported design is that of A. P. Senchenkov and F. M. Kuznetsov [10], who have designed a selector with disks with phase shifted openings, consisting of 19 central (symmetrical) disks and two asymmetrical end disks (fig. 12).

As in the case of the Jacrot and Gobert selector, the rotor is placed in a vacuum. The length of the rotor is 53 cm, the diameter 27 cm, and its weight 55 kg. The speed may reach as high as 12,000 rpm, the selector being designed for operation in the energy range under 0.5 ev.

There are 297 openings over the circumference of the rotor, each opening being 0.8 mm wide and 13 mm thick. Their normal forms an angle of 1.6° with the generatrix of the cylinder on which the curves described by the openings are inscribed. The speed is variable, the usual operating range being included between 2,500 and 9,500 rpm.

Neutron detection is effected with the aid of a counter filled with boron trifluoride (BF_3) under a pressure of 600 mm Hg, and having the dimensions of 250 mm in length and 35 mm in diameter. (The dimensions of the counter are highly important in transit time technique, inasmuch as it is principally counter length which determines the systematic error.)

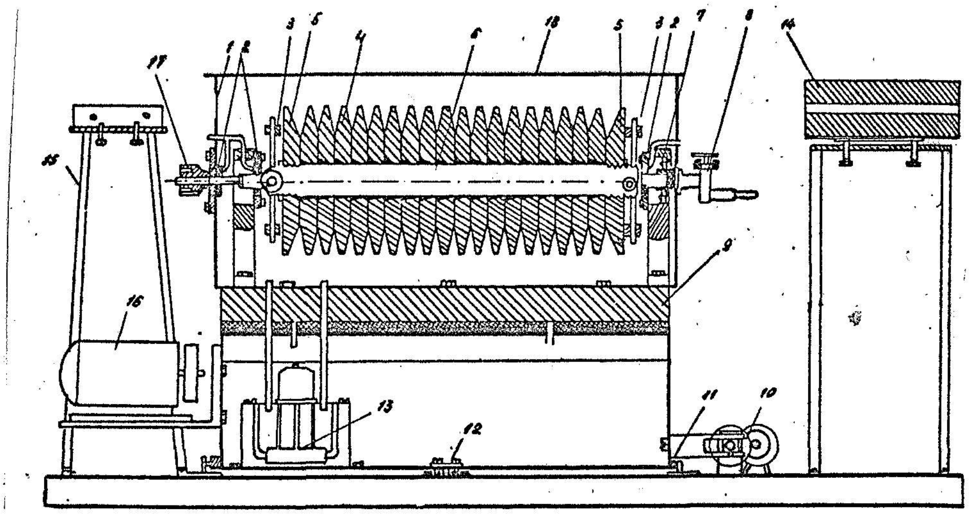

Fig. 12. Cross section of monochromator designed by Senchenkov and Kuznetsov: 1 — aluminum window; 2 - rotor bearings; 3 — speed regulator; 4 — disks; 5 — end disks; 6 — motor shaft; 7 — tachometer; 8 — vacuum installation cock; 9 — bedplate; 10 — bedplate rotating mechanism; 11 — transmission; 12 — bearings; 13 — oil pump; 14 — detector housing; 15 — collimator support; 16 — electromotor; 17 — rotor transmission; 18 — evacuated enclosure.

The authors establish for this particular case a series of formulas which determine the performance of the selector; specifically:

(a) The velocity of the selected neutrons v is given by the relation

$$v = \frac{v_{rot} \cos \alpha_2}{\sin \alpha_1}, \tag{4}$$

in which v_{rot} is the linear velocity of the center of an opening, which may be approximated by the linear velocity of the circumference of the rotor; α_2 the angle between the normal of an opening and the generatrix of the cylinder ($\alpha_2 = 1.6^\circ$); and α_1 the angle between the normal of the opening and the direction of the neutron beam ($\alpha_1 \leqslant 5^\circ$).

(b) The resolving power of the selector is given by the formula

$$\frac{\Delta E}{E} = \frac{2v}{v_{rot}} \sqrt{\left(\frac{d_{rot}}{l_{rot}}\right)^2 + \left(\frac{d_{col}}{l_{col}}\right)^2 + \left(0{,}65 \frac{h_{rot}\, v_{rot}}{R_{rot}\, v}\right)^2}, \tag{5}$$

in which $\underline{E}$ is the energy for which the resolving power is calculated; ΔE the half-width of the selected energy band; d_{rot} and d_{col} the widths of the rotor and collimator openings; l_{rot} and l_{col} the depths of the rotor and collimator openings; h_{rot} the effective height of the rotor opening (which is actually exposed to the neutron beam); and R_{rot} the radius of the rotor.

(c) The number of neutrons at the selector output is determined by these authors by the approximating formula

$$N = \frac{h_{col}\, d_{col}}{8\pi l_{col}^2} \frac{h_{rot}\, d_{rot}}{d_{rot} + D_{rot}} \Phi(E)\, \Delta E, \tag{6}$$

in which $\Phi(E)$ is the neutron flux in the energy interval equalling unity and D_{rot} is the distance between the rotor openings.

4. CALCULATION OF RESOLVING POWER OF HELICAL SELECTOR

According to Dash and Sommers [4], the theoretic approximation which corresponds the best to the real situation is that which assumes the following hypotheses to be satisfied:

- the channels are helical;
- the openings are of finite width;
- the neutron beam is divergent.

If the angle of divergence of the beam equals α, Dash and Sommers define a "quality factor" of the device equalling

$$F = \frac{\Delta\lambda + \epsilon_0}{\bar{\lambda}}, \tag{7}$$

in which $\epsilon_0 = \frac{h\alpha_0}{m\omega R_0}$, $\Delta\lambda = k\,\Phi$, where $\underline{k}$ is found from the relation

and $\bar{\lambda}$ is the average wavelength; Φ the aperture angle of the openings; $\underline{m}$ the mass of the neutron; ω the angular velocity of the rotor; R_0 the radius of the rotor; and $\underline{h}$ Planck's constant.

These authors assert that it is very difficult to calculate the resolving power, if not practically impossible; it is for this reason that they have introduced the "quality factor." In what follows we shall endeavor to make an approximated calculation of the resolving power of the helical selector.

We shall refer to the selector in which the channels are straight and parallel to the generatrix of the cylinder, the entire device being set at an angle to the direction of the neutron beam (fig. 6a) and equivalent to the one in which the channels are at an angle to the generatrix, the latter being parallel to the direction of the neutron beam (fig. 6b).

We are to imagine an opening of the selector (fig. 6a); the first point encountered by the beam is point A; the fastest neutrons quickly travel through the channel, following a path (in a mobile system, and thus relative to the opening) nearly parallel to the wall 1; they leave through point A'. However, the beam also contains slow neutrons. The slowest neutrons, which enter through point A, leave through B'; that is, they follow the path AB', taking the greatest time (of all the neutrons entering the channel) to travel through the channel.

Throughout the period during which the opening is "open," that is, the neutrons enter the channel through the points situated between points A and B, the channel will be traversed only by the neutrons which are not fast enough to reach and strike wall 1 and are not slow enough to be hit by wall 3.

The neutrons traversing the channel will follow intermediate paths between walls 1 and 3, that is, any line which connects a point on the segment AB with a point on the segment A'B' may (potentially) be the path of a neutron traversing the channel, since this path fulfills the passage condition, which requires that the "points" of the path in the mobile system (that is, converging straight lines) coincide successively and uniformly in time with the direction of the beam in the fixed system (the direction designated $_0n^1$ in fig. 6a).

To see which are the fastest neutrons, the ones which continue to traverse the channel, we post ourselves at point B; the fastest neutrons, which enter through this point, will reach wall 1 only at point A, following path 4.

Then, knowing that the time in which the neutrons traverse the distance L (equal to the length of the rotor) equals the time in which the rotor is rotated through angle ϑ, we can write:

— for the fastest neutrons (path 4)
$$\vartheta = \omega t,\ t_r = \frac{L}{v_r} = \frac{\vartheta}{\omega},$$

— for the slowest neutrons (path 2)
$$t_l = \frac{L + \Delta L}{v_l} = \frac{\vartheta + \Delta\vartheta}{\omega} = t_r + \Delta t,$$

that is,

$$v_r = \frac{L\omega}{\vartheta},$$

$$v_l = \frac{(L + \Delta L)\,\omega}{\vartheta + \Delta\vartheta}. \tag{8}$$

We thereby obtain the resolving power in terms of selector speed:

$$P_v = \frac{\Delta v}{v} = \frac{v_r - v_l}{v_r} = 1 - \frac{\dfrac{L+\Delta L}{\vartheta + \Delta\vartheta}\,\omega}{\dfrac{L}{\vartheta}\,\omega} \approx 1 - \left(1 - \frac{\Delta\vartheta}{\vartheta}\right)\left(1 - \frac{\Delta L}{L}\right) \approx \frac{\Delta\vartheta}{\vartheta} - \frac{\Delta L}{L}. \quad (9)$$

In terms of energy we may write

$$P_E = 2\,\frac{\Delta v}{v},$$

since $E = \frac{1}{2} m v^2$, $\ln E = 2 \ln v$, whence $\frac{\Delta E}{E} = 2\,\frac{\Delta v}{v}$.

Proceeding now to the case of figure 6b, we note that we can write

$$P_v \simeq \frac{\Delta\vartheta}{\vartheta},$$

inasmuch as $\Delta L = 0$.

Writing $\operatorname{tg} \Delta\vartheta \simeq \Delta\vartheta$, since angle $\Delta\vartheta$ is small, from

$$\operatorname{tg}\,\Delta\vartheta = \frac{S\cos\vartheta}{\dfrac{L}{\cos\vartheta}}$$

we find (see fig. 6b)

$$P_v = \frac{S\cos^2\vartheta}{\vartheta},$$

in which S is the width of the channel opening.

It is seen that this expression, which is a function only of θ, admits a maximum for θ given by the expression

$$\left(\frac{\partial P}{\partial\vartheta}\right)_{S=\mathrm{const}} = S\,\frac{2\vartheta\sin\vartheta\cdot\cos\vartheta - \cos^2\vartheta}{\vartheta^2} = 0,$$

which gives us $\vartheta = 0,\ \vartheta = 90°$ (the minimum; from the physical standpoint it is obvious that if the channel is perpendicular to the direction of the beam, no neutron will pass through the channel) and the equation

$$\vartheta = -\operatorname{ctg}\vartheta,$$

which, solved in approximation (graphically), gives us $44° < \vartheta_{\mathrm{opt}} < 47°$.

We shall take $\vartheta_{optim} \approx 45°$, this being the angle for which the resolving power is the maximum.

Since the resolving power is directly proportional to the width of the opening S, it is to be seen that the resolution is the better, the smaller is the width of the opening, as was to be expected. In this case, however, there is a great drop in transparency and a compromise must be reached between the two requirements:

— good resolution and

— good transparency,

which are contradictory.

5. TRANSPARENCY

One sometimes speaks of the "luminescence" of a selector, but since luminescence is a physical and physiological quantity, we shall operate with the quantity designated "transparency" or "transmission."

The transparency or transmission coefficient of any selector, independently of whether a "low-pass," "high-pass," or "band-pass" filter is involved, is understood to mean a number (having no physical dimensions) which represents the ratio of the number of neutrons passing through a filter to the number of incident neutrons.

Under constant conditions this ratio does not depend on time; in what follows we shall use either the term transparency or the term transmission, the two being equivalent.

Let us consider a device (such as are the neutron selectors) through which the neutrons pass only a fraction f_t of the time; it is said that the device is "open" during this time.

If the incident neutrons have an energy spectrum included between E_1 and E_2, and the neutrons which "pass through" have a spectrum included between E_{min} and E_{max}, we can then define the fraction (in terms of energy), f_E, of the number of neutrons which traverse the device.

The number of incident neutrons, defined in terms of energy is $\int_{E_1}^{E_2} n(E)\, dE$, (in case I, $E_2 \to \infty$, see Fig. 13); the number of neutrons which traverse the device is $\int_{E_{min}}^{E_{max}} k(E)\, n(E)\, dE$. The transparency or transmission of the device may then be written

$$T = f_t \cdot t_E = f_t \frac{\int_{E_{min}}^{E_{max}} k(E)\, n(E)\, dE}{\int_{E_1}^{E_2} n(E)\, dE}. \tag{10}$$

In (10) k(E) represents the ratio of segment AB to AC (fig. 13), inasmuch as in theory all neutrons of energies between E_{min} and E_{max} pass through, while in reality only very few pass through, those in the cross-hatched area (fig. 13); k(E) is usually found by experiment, and is < 1.

Its appearance is due to the "end effects," that is, to the fact that the openings open gradually in time, and not abruptly, by jumps (only in this case would we have $k(E) = 1$).

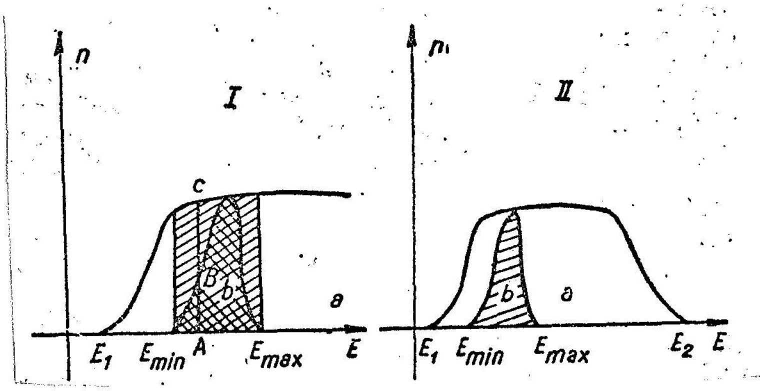

Fig. 13. Distribution of neutrons according to energy, before selection (a) and after (b), in the ideal case in which the spectrum extends to infinity (I) or to a maximum energy E_2 (II).

It is obvious that the relationship between the two integrals represents the relationship between the two areas (shaded and cross-hatched) in figure 13.

It is to be seen that if the entire spectrum is transmitted, $f_E \rightarrow 1$, and if transmission were to take place constantly, $f_t \rightarrow 1$; in this case all the neutrons pass and $T \rightarrow 1$, that is, the general conditions for transparency are fulfilled: $T \leqslant 1$ and, at the limit, when $f_E \rightarrow 1$ and $f_t \rightarrow 1$, $T \rightarrow 1$.

The fraction of time during which the device is open is calculated as follows.

Let there be a rotary device having $\underline{a}$ openings disposed radially (fig. 14a) or peripherally over the frontal surface of the device which the neutrons strike (such as in the case of the device in fig. 14b).

Such a rotary device opens $\underline{a}$ times per complete rotation.

The fraction of time (within one second) during which the neutrons pass may be calculated immediately.

We have $\underline{a}$ pulses in a complete rotation. If the rotor executes $\underline{n}$ revolutions per minute, that is, $\frac{n}{60}$ revolutions per second, $\frac{an}{60}$ pulses pass in one second. A pulse lasts through the time during which a length $\underline{S}$ on the surface passes through the plane of fixed point A, that is, $\Delta t = \frac{S}{\omega R}$ seconds.

In one second $\frac{an}{60}$ pulses pass through, that is, we have a fraction of a second during which the selector is open,

$$\frac{t'}{1\ \text{sec}} = \frac{an}{60}\Delta t = \frac{an}{60}\cdot\frac{S}{\omega R} \quad \text{(fractions of a second)}$$

or

$$\frac{t}{1 \text{ sec}} = \frac{an}{60} \frac{S}{\frac{an}{60} R} = \frac{aS}{2\pi R}.$$

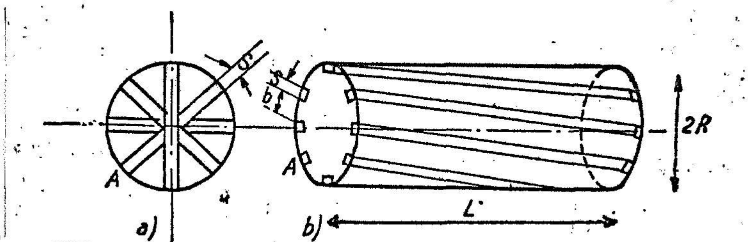

Fig. 14. Compar[illegible] selector as neutron beam choppers: (a) chopper opening eight times per complete rotation; (b) helical selector with eight openings per revolution. The former functions as a "low-pass" filter, and the latter as a "band-pass filter."

This fraction corresponds to the time function f_t. It may also be found directly, from the consideration that for a point A the circumference presents within one second an "open" portion, aS, relative to the total length of the circumference, $2\pi R$. That is to say, the probability that the neutrons will enter the selector is $\frac{aS}{2\pi R}$, which corresponds to the time function f_t.

The transmission is thus a probability of the "and-and" type which is expressed by the product of the two probabilities f_t and f_E.

We may write

$$T = \frac{aS}{2\pi R} \cdot \frac{\int_{E_{\min}}^{E_{\max}} K(E)\, n(E)\, dE}{\int_{E_1}^{E_2} n(E)\, dE}. \tag{11}$$

When $S \longrightarrow 0$, $T \longrightarrow 0$, that is, the condition that the rotor become opaque to neutrons when the entrance openings become infinitely small, is also fulfilled.

Dash and Sommers [4] calculate a coefficient τ which they designate "transmission fraction" and which corresponds to the function f_t found above. It is obvious that the transparency T, defined at point 4, describes the selector qualities more completely.

6. THE TRANSMISSION FUNCTION CALCULATED BY DASH AND SOMMERS [4]

The calculation hypotheses are the following: helical channels, opening of finite width, and parallel neutron beams.

Case I. The spectrometer is made up of a identical helical channels, with a spacing of $\frac{L}{\vartheta}$, whith rotate at angular velocity ω. Each opening has an angular aperture Φ; the fraction of the incident beam which enters an opening (channel) will then be

$$\tau_0 = \frac{aR\Phi}{2\pi R} = \frac{a\Phi}{2\pi} \left(\equiv \frac{aS}{2\pi R}, \text{ the expression found previously}\right).$$

From $\lambda = \frac{h}{p}$, in which λ is the associated wavelength, h Planck's constant, and p the impulse of the incident neutron, and bearing in mind that $t = \frac{\vartheta_0}{\omega} = \frac{L}{v}$, we find

$$\lambda_0 = \frac{h}{m\omega} \frac{\vartheta_0}{L} \equiv k\vartheta_0 .$$

The path of the neutrons of wavelength λ_0 is parallel to the edge of the channel (fig. 15, path designated λ_0).

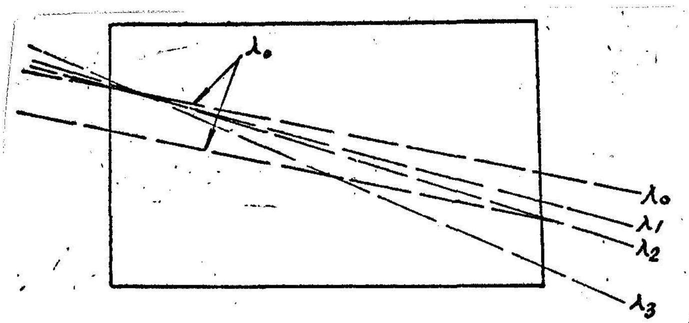

Fig. 15. Path of neutrons relative to opening in a system of coordinates rigidly connected to the opening.

The neutrons of any wavelength $\lambda = \lambda_0 + k\delta\Phi$ traverse the opening while following paths , etc (fig. 9). For the neutrons which traverse the channel without colliding with the edges of the latter, the channel appears as a relatively diminished aperture $R\Phi - R|\delta\Phi|$ in magnitude. The transmission will be

$$\tau(\lambda) = \frac{a(R\Phi - R|\delta\Phi|)}{2\pi R} = \frac{a(\Phi - |\delta\Phi|)}{2\pi} .$$

Consequently

$$\delta\vartheta = \frac{\lambda - \lambda_0}{k}, \text{ and } \tau_0 = \frac{a\Phi}{2\pi},$$

so that

$$\tau(\lambda) = \tau_0\left(1 - \frac{\lambda - \lambda_0}{k}\right)\left(\equiv f_t \cdot f_E, \quad \text{in which it is seen that } f_t \equiv \tau_0, f_E = 1 - \frac{\lambda - \lambda_0}{k}\right).$$

Noting that $k\Phi = \Delta\lambda$, we find

$$\tau(\lambda) = \tau_0\left(1 - \frac{\lambda - \lambda_0}{\Delta\lambda}\right), \quad \text{for } |\lambda - \lambda_0| \leqslant \Delta\lambda,$$
$$\tau(\lambda) = 0, \quad \text{for } |\lambda - \lambda_0| > \Delta\lambda.$$

The "transparency" from the preceding point and the "transmission" from this point are one and the same thing, but we have retained the term transmission because it was the one employed by these authors in the original article.

<u>Case II</u>. This time it is assumed that the spectrometer is exposed to a beam of neutrons of an angular aperture of $2\alpha_0$. It then follows that the relative aperture of the opening diminishes owing to the divergence of the beam, specifically, by $L\alpha$; in this case [4] the transmission will be

$$\tau(\alpha, \lambda) = \tau_0\left\{1 - \frac{\left|\lambda - \lambda_0 + k\frac{L}{R}\alpha\right|}{\Delta\lambda}\right\}, \quad \text{for } \left|\lambda - \lambda_0 + k\alpha\frac{L}{R}\right| \leqslant \Delta\lambda,$$
$$\tau(\alpha, \lambda) = 0, \quad \text{for } \left|\lambda - \lambda_0 + k\alpha\frac{L}{R}\right| > \Delta\lambda.$$

The transmission of the spectrometer as a function only of λ is found by averaging over α:

$$\tau(\lambda) = \frac{\int_{-\alpha}^{+\alpha} \tau(\lambda, \alpha)\, d\alpha}{\int_{-\alpha}^{+\alpha} d\alpha}.$$

Dash and Sommers have found by experiment that this case (divergent neutron beam with $2\alpha_0$) approximates the best real situation.

Designating $\epsilon_0 = \frac{kL\,\alpha_0}{R_0} = \frac{h}{m\omega}\cdot\frac{\alpha_0}{R_0}$, in which α_0 and R_0 are the data of the problem (that is, a certain divergence α_0 of the beam and a certain radius R_0 of the rotor), and choosing as a parameter the quantity in which is the aperture of the opening and S its width), they found the transmission functions shown in figure 16 for the helical selector.

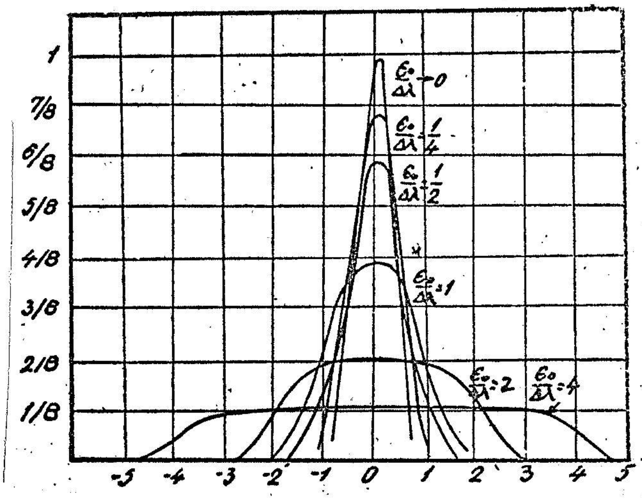

Fig. 16. Transmission function calculated by Dash and Sommers: $[\tau(\lambda)]_{\epsilon_0/\Delta\lambda = \text{const.}} = f(x)$, $x = \lambda - \lambda_0$.

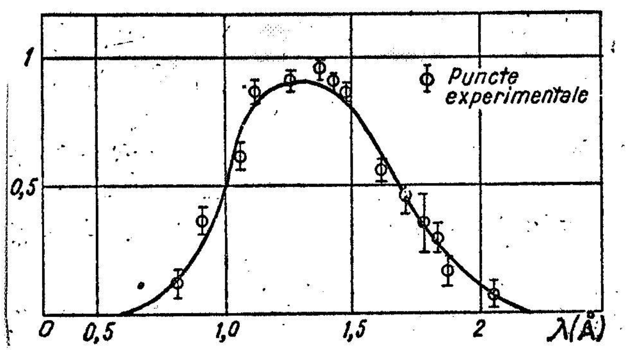

Fig. 17. Form of transmission function $\tau(\lambda)$ of helical selector. The calculation was made for $\epsilon_0/\Delta\lambda = 1{,}0$ and F = 0.6, with a 320 °K thermal neutron source. [Intensitatea relativa a fluxului de neutroni = Relative intensity of neutron flux; Puncte experimentale = Experimental points.]

The transmission function of the spectrometer may be measured experimentally by means of the device shown in figure 4.

The values found by experiment agree fairly well with the calculated values (see fig. 17).

7. PLANNING

It is of interest for planning purposes to calculate the relationship of transparency to resolving power; for its calculation we shall employ the expressions

$$P = S\frac{\cos^2\vartheta}{\vartheta}, \quad \vartheta = 45^\circ = \text{const.}$$

and

$$\tau_0 = \frac{a\Phi}{2\pi} = \frac{aS}{2\pi R}.$$

The transmission in time for a given energy is the product of the length of a pulse $\left(\frac{S}{\omega R}\right)$ and the number of pulses per second , that is, it equals $\frac{aS}{2\pi R}$. We have seen that the transmission in energy is always less than one and cannot be calculated exactly. For this reason we shall consider it for a given energy to be equal to a constant $C < 1$; the quotient with which we are concerned will then be

$$\frac{T}{P} = C\frac{\frac{aS}{2\pi R}}{S\frac{\cos^2\vartheta}{\vartheta}} = C\frac{a}{2\pi}\frac{\vartheta}{\cos^2\vartheta}.$$

Inasmuch as the transparency must be the maximum and the inverse of the resolving power must also be the maximum, this ratio $\frac{T}{P}$ must be the maximum.

As was to be expected, this ratio does not depend on the width of the opening S, so that we are always obliged to choose a compromise solution, good transparency entailing poor resolution and vice versa. The ratio depends only on the variable ϑ.

The maximum condition for the ratio in question is written

$$\cos\vartheta + 2\vartheta\sin\vartheta = 0.$$

This condition coincides with the maximum condition for the resolving power; we have found the solution $44^\circ < \vartheta_{opt} < 47^\circ$. We shall thus adopt for symmetry in planning, the angle being measured on the evolute of the cylinder.

Progress of the calculation. The following are generally given:

— the speed of the neutrons, v (or their energy, E),

— the length of the rotor, L,

— the depth of the opening, equalling the transverse dimension of the incident beam, $2H$,

— the number of openings (channels), a.

We have seen that the magnitude of the angle is found from the maximum condition of the resolving power, which gives

$$\vartheta_{\text{opt}} \approx 45°.$$

To determine the width of the opening, S, we shall plot both the transparency T and the resolution (the inverse of the resolving power) $\frac{1}{P}$ in the same diagram. The expression for the transparency T is

$$T = \frac{aS}{2R} \cdot \frac{\int_{E_{\max}}^{E_{\min}} k(E)\, n(E)\, dE}{\int_{E_1}^{E} n(E)\, dE} = k_1 S,$$

if we retain only the dependence on S.

The resolution is written

$$\frac{1}{P} = \frac{\vartheta}{\cos\vartheta} \cdot \frac{1}{S} = k_2 \cdot \frac{1}{S}$$

With T and $\frac{1}{P}$ plotted against S (fig. 18), it was seen that the two functions are equal for a certain value of opening width S. When S increases the transparency is better, but the resolution decreases. The opposite situation prevails when S decreases.

Knowing certain initial data, we have thus determined the energy band which may be extracted from the spectrum. For this purpose we have determined a value which we consider the optimum for the width of the opening and the angle of inclination of the channel, employing a maximum condition (for θ) and a compromise condition (for S).

Finally, the angular velocity ω was determined from the operating condition

$$t = \frac{L}{v} = \frac{\vartheta}{\omega},$$

itself.

All the essential quantities were thus determined. It is obvious that the calculations may also be based on other quantities, but there is no fundamental difference between the two possible methods of calculation.

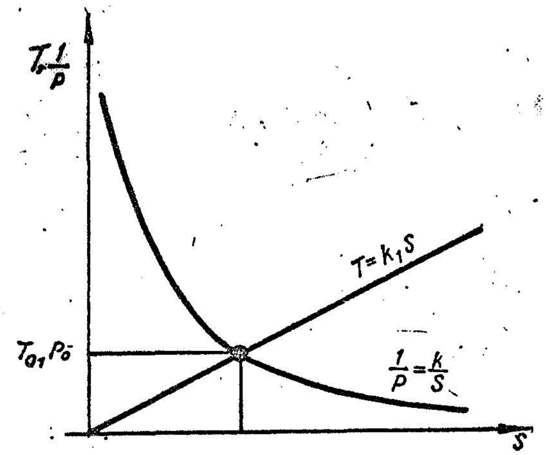

Fig. 18. Transparency T and resolution $\frac{1}{P}$ versus width of opening S.

After the calculations have been carried out, we must ascertain whether the thickness of the material presented by the fast neutron selector is sufficient to give us an opacity of the order of 10^{-4} to 10^{-6}. The condition

$$\frac{N}{N_0} = e^{-\Sigma x} \leqslant 10^{-4} \div 10^{-6},$$

in which Σ is the total effective section and x the thickness of the material, must be fulfilled for this purpose. The condition gives us

$$\Sigma x \geqslant 12{,}9, \quad \text{for the case of } 10^{-6}.$$

If we have several materials arranged successively (steel ribs — cadmium-plated openings), the condition is written

$$\frac{N}{N_0} = e^{-\Sigma_1 x_1} \cdot e^{-\Sigma_2 x_2} \ldots e^{-\Sigma_n x_n} \leqslant 10^{-6},$$

this giving us

$$\Sigma_1 x_1 + \Sigma_2 x_2 + \ldots + \Sigma_n x_n \geqslant 12{,}9.$$

If the condition is not fulfilled, we must:
— either adopt a material of greater thickness (thicker ribs),
— or adopt a material with a greater effective cross section.

If these solutions are not possible, the selector must be redesigned, that is, the geometric dimensions must be reconsidered.

CONCLUSIONS

1. The helical selector is characterized by good transmission (to around 80%); in this case, however, the resolution is poor.

The selector is used in conjunction with a crystal spectrometer (fig. 4) to achieve good resolution.

2. In theory, such a selector can have a resolving power as good as is desired; in practice, however, the decrease in transmission accompanying increase in resolving power causes a limitation which is the more rapid, the weaker is the source.

Hence the problem of obtaining good resolving power is linked to the problem of obtaining sources as intense as possible. Generally speaking, good resolution can be obtained when one operates with small transmission.

3. It is to be seen from the foregoing that the range of employment of this type of selector is the thermal range. Theoretically, the selector functions in any range, but we are limited to the thermal range because:

— the speed of rotation cannot be as high as desired (in practice the speed does not exceed 15,000 to 20,000 rpm);

— the opacity of the selector decreases exponentially when the speed of the neutrons increases;

— if we wish to employ the device consisting of a selector plus a crystal spectrometer, we cannot exceed the limit of around 10 ev, beyond which the resolution of the crystals decreases very rapidly.

These factors hold us to the range of thermal neutrons.

4. We may add that this type of selector is stable in operation and that it presents the advantage of being relatively easy to plan and design.

5. In the introduction to this article it was stated that the helical selector did not evolve directly through the disk selector; this is supported by the fact that such selectors were not designed until 1957-1958. It is probable that their creation involved great technical difficulties, this greatly delaying the appearance and development of selectors of this type.

The last two types of selectors, [9] and [10], represent the most highly developed types of disk selectors; their designing forms part of the general effort to determine with greater precision the effective cross-sections of the energy range of epithermal, thermal, and cold neutrons. Effort being aimed today especially at determination of the effective cross-sections of the elements for cold neutrons, such determination will probably clarify some of the problems of interaction between neutrons and nuclei, and will possibly create some light in the problem of nuclear forces, which has been subjected to so much discussion.

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